Historic Overview of Algal Blooms in Marine and Estuarine Waters of New South Wales, Australia

PENELOPE AJANI[1], GUSTAAF HALLEGRAEFF [2] AND TIM PRITCHARD[1]

[1]Water Science Section, Environment Protection Authority, New South Wales, PO Box A290 Sydney South, NSW, 1232, Australia
[2]School of Plant Science, University of Tasmania, GPO Box 252-55, Hobart, Tasmania, 7001, Australia

Ajani, P., Hallegraeff, G. and Pritchard, T. (2001). Historic overview of algal blooms in marine and estuarine waters of New South Wales, Australia. *Proceedings of the Linnean Society of New South Wales* **123**, 1-22.

A compendium of algal bloom reports for marine and estuarine waters of New South Wales, Australia, for the period 1890-1999 is presented. The majority of blooms have been harmless water discolourations predominantly caused by the large heterotrophic dinoflagellate *Noctiluca scintillans*, or the filamentous cyanobacterium *Trichodesmium erythraeum*. Other harmless species that have bloomed include the dinoflagellates *Gymnodinium sanguineum* (= *Akashiwo sanguinea*) and *Prorocentrum minimum*, the surf diatom *Anaulus australis*, the coccolithophorid *Gephyrocapsa oceanica* and the ciliate *Mesodinium rubrum*. Species that have produced blooms and are potentially harmful to marine organisms include the silicoflagellate *Dictyocha octonaria*, the dinoflagellates *Gonyaulax polygramma* and *Scrippsiella trochoidea* and the diatoms *Thalassiosira* spp. and *Chaetoceros* spp. The toxic raphidophyte species *Heterosigma akashiwo*, *Chattonella* cf *globosa* and *Haramonas* sp., the dinoflagellates *Gymnodinium galatheanum* (= *Karlodinium micrum*), *Dinophysis acuminata* and *Alexandrium catenella*, and the diatoms *Pseudo-nitzschia multiseries* and *P. australis* have also been identified as bloom-forming species in these waters.

Reports of algal blooms have apparently increased considerably since 1990 but the data may be biased because of the *ad hoc* nature of these reports. For this reason it is difficult to identify the cause(s) of this apparent increase in bloom frequency. Contributing factors may include the expansion in coastal settlements, an increase in awareness of environmental issues such as water quality, possible changes in anthropogenic nutrient input and/or the effects of large-scale oceanographic phenomena and/or climate change.

Manuscript received 22 August 2001, accepted for publication 24 October 2001.

KEYWORDS: algal bloom, ciliate, coccolithophorid, cyanobacterium, diatom, dinoflagellate, estuaries, raphidophyte, silicoflagellate.

INTRODUCTION

Fluctuations in the nutrient status of coastal waters, either of natural origin or associated with anthropogenic disturbances, can lead to changes in species composition and abundance of marine and estuarine microalgae. This may result in algal blooms that threaten fish resources, human health and ecosystem function and the recreational amenity of beaches and embayments. Other algal blooms are simply harmless, transient pulses in response to episodic nutrient enrichment such as from coastal upwelling events (Smayda 1997). Whatever factors affect their formation, the focus on algal blooms is increasing.

Global evidence is emerging of an apparent increase in the distribution and frequency of algal blooms (Hallegraeff 1993).

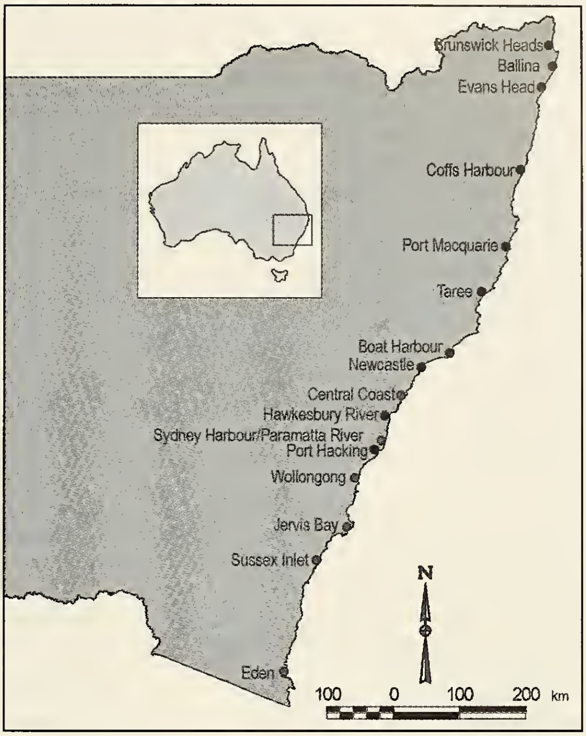
Eutrophication can lead to enhanced phytoplankton growth (including nuisance and/or toxic algal blooms) or a change in the species composition of phytoplankton and other organisms (Oviatt et al. 1989; Graneli and Moreira 1990; Riegman et al. 1992; Pan and Rao 1997). Hallegraeff reviewed harmful algal blooms in the Australian region in 1992 and suggested that from the 1970s to the 1990s there had been an escalation of harmful blooms in Australian marine and estuarine waters. Consequently, algal blooms have been targeted as a key environmental indicator for long term monitoring in Australian waters (Ward et al. 1998). There is, however, no systematic reporting of algal blooms in New South Wales (NSW) marine and estuarine waters.

The NSW coastline is 1,900 km in length and ranges from warm subtropical in the north to cool temperate in the south (Fig. 1). It has approximately 700 beaches; with large sandy beaches in the north and smaller pocket beaches bounded by rocky headlands in the south. It is naturally divided into three regions based on broad oceanographic characteristics and the geological structure of the coastline (EPA 1995). The northern region is under the dominant influence of the warm East Australian Current, while the cooler waters and currents from Bass Strait influence the southern region. The central region is a mixed zone. The majority of the human population (6.3 million) is concentrated in the central zone in three major cities, Sydney, Newcastle and Wollongong, and all of these cities are associated with major estuaries. Increased pressures on the entire NSW coastal zone (population increase and coastal development, tourism, water quality and sewage disposal) mean that the potential for algal blooms is increasing. The NSW aquaculture industry, presently worth $42-45 million, is projected to increase to $250 million by 2010.

A three-year ocean nutrient and phytoplankton study carried out by the New South Wales Environment Protection Authority (NSW EPA) has been completed recently (1995-1998). That study characterised ambient nutrient concentrations and more specifically, identified the relative significance of various sources of nutrients in NSW offshore coastal waters. The focus of the investigation was on the extent of slope water intrusions and their associated nutrient concentrations, comparing this to anthropogenic nutrient inputs, including the three major deepwater ocean outfalls and estuarine discharges. Phytoplankton blooms at various locations along coastal NSW were related to this information. As part of this study the Commonwealth Scientific and Industrial Research Organisation (CSIRO) long-term 100m coastal station off Port Hacking was revisited in 1997-98 to investigate phytoplankton patterns and their hydrological environment and to compare these patterns to previous investigations at the same location (Ajani et al. 2001). It is useful to discuss recorded algal blooms in light of these data, as well as the links found between the environmental variables (factors which may promote algal blooms) and the phytoplankton community composition.

Three types of algal blooms can be distinguished - those that are harmless water discolourations, potentially harmful to marine organisms (although non-toxic) or potentially toxic to humans. Human illness associated with harmful algae is due to the naturally occurring toxins which are transferred to humans through the consumption of seafood products. The most significant public health problems caused by harmful algae are Amnesic Shellfish Poisoning (ASP), Ciguatera Fish Poisoning (CFP), Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NSP) and Paralytic Shellfish Poisoning (PSP). Each of these syndromes is the result of different causative organisms that produce a range of toxins and risks to humans. These have been discussed by various authors (Taylor 1990; Hallegraeff 1991, 1992, 1993; Smayda 1997). Except for ASP (which is caused by diatoms), all other syndromes are caused by biotoxins synthesised by dinoflagellates.

Figure 1. Map of New South Wales coastal zone



Potentially toxic phytoplankton are not always toxic in every situation and it is anticipated that in the future other phytoplankton species may prove to be toxic under certain conditions (UNESCO 1995). In addition, the factors that promote algal populations to significantly increase (deviate from their normal cycle of biomass, i.e. to 'bloom') are varied. A range of physical, chemical and biological variables are involved and there may be quite different bloom determinants depending on the type and location of the water body (eg estuarine versus offshore waters).

Methods and Data Assessment

This paper discusses visible bloom events that have been recorded in NSW marine (coastal and offshore) and estuarine waters. Various NSW government agencies, local councils, water authorities, universities and the public have contributed to these data. Published references to these blooms have been used wherever possible. Other data have been collated from NSW Environment Protection Authority [formally the State Pollution Control Commission (SPCC)] unpublished file reports and similar reports from Australian Water Technologies (AWT). Suitably qualified scientific officers (including the authors) identified the causative organisms in these bloom incidents. Blooms listed as "unidentified" were not examined by scientific officers for various reasons such as no sample was collected or because of sample deterioration prior to examination. Other potentially harmful species have also been identified in these waters but have not yet reached bloom proportions. These are also referenced and discussed.

Table 1. Harmless algal blooms recorded in New South Wales's marine (M) and estuarine (E) waters

Date	*Location*	*Bloom Taxa*
July- Aug 30-32	Sydney Harbour (E)	*Gymnodinium sanguineum*[1]
Oct-72	Taree and Coffs Harbour (M)	*Trichodesmium* sp[3]
Dec-72	Palm Beach to Cronulla (M)	*Trichodesmium* sp[3]
Oct-80	Alexandra Canal (Cooks River, Sydney) (E)	*Gymnodinium sanguineum*[3]
Oct-81	Lane Cove River (Sydney) (E)	*Gymnodinium sanguineum*[3]
Aug-82	Lake Macquarie (Central Coast) (E)	*Noctiluca scintillans*[3]
Dec-83	Newcastle, Narrabeen, Foster, Bondi Beach (M)	*Trichodesmium* sp[3]
Apr-84	Lane Cove River (Sydney) (E)	*Mesodinium rubrum*[3]
Nov-84	Lane Cove River (Sydney) (E)	*Mesodinium rubrum*[3]
Dec-84	Sydney to Wollongong (M)	*Trichodesmium sp*[3]
Feb-86	Lane Cove River (Sydney) (E)	*Mesodinium rubrum*[3]
Jan-89	Sydney coastal waters and Jervis Bay toUlladulla (M)	*Trichodesmium* sp[3]
Aug-92	Lake Macquarie (Central Coast) (E)	*Noctiluca scintillans*[3]
Sep-92	Berowra Creek (Hawkesbury River) (E)	*N. scintillans/G. sanguineum*[3]
Dec-92	Jervis Bay (M)	*Gephyrocapsa oceanica*[2]
Jan-93	Sydney beaches and Port Kembla (M)	*Noctiluca scintillans*[3]
Jun-93	Lake Illawarra (E)	*Noctiluca scintillans*[4]
1994	Berowra Creek (Hawkesbury River) (E)	*Gymnodinium sanguineum*[4]
Feb-94	Sydney northern beaches (M)	*Noctiluca scintillans*[4]
Apr-94	Ham & Chicken Bay (E)	*Noctiluca scintillans*[3]
Jul-94	Berowra Creek (Hawkesbury River) (E)	*Pseudonitzschia pungens*[4]
Nov-94	Sydney northern beaches (M)	*Noctiluca scintillans*[4]
Nov-94	Offshore from Port Hacking and Wollongong (M)	*Noctiluca scintillans*[4]
Nov-94	Narrabeen Lakes (Sydney) (E)	*Noctiluca scintillans*[4]
Dec-94	Newcastle Beach (M)	*Noctiluca scintillans*[4]
Dec-94	Jervis Bay (M)	*Noctiluca scintillans*[4]
Mar-95	Pearl Beach (Sydney) (M)	*Noctiluca scintillans*[4]
Mar-95	Berowra Creek (Hawkesbury River) (E)	*Prorocentrum minimum*[4]
Aug-95	North Harbour (Sydney) (M)	*Gymnodinium sanguineum*[4]
Sep-95	Offshore from Sydney Heads (M)	*Noctiluca scintillans*[4]
Oct-95	Offshore from Boat Harbour and Anna Bay (M)	*Trichodesmium erythraeum*[4]
Feb-96	Stanwell Park to Astinmer (M)	*Noctiluca scintillans*[4]
Feb-96	Wamberal Beach (Central Coast) (M)	*Noctiluca scintillans*[4]
Mar-96	Sussex Inlet (E)	*Noctiluca scintillans*[4]
Mar-96	Paradise Beach (St Georges Basin) (E)	*Noctiluca scintillans*[4]
Mar-96	Hymans Beach (Jervis Bay)	*Noctiluca scintillans*[4]
Mar-96	Sussex Inlet (E)	*Noctiluca scintillans*[4]
Aug-96	Shelley Beach (Manly) (M)	*Mesodinium rubrum*[4]
Aug-96	Greenwich Baths (Parramatta River) (E)	*Mesodinium rubrum*[4]
Oct-96	Offshore from Boat Harbour and Anna Bay (M)	*Trichodesmium erythraeum*[4]
Oct-96	Port Stephens to Broughton Island (M)	*Trichodesmium erythraeum*[4]
Oct-96	Manly (Sydney) (M)	*Noctiluca scintillans*[4]
Jan-97	Sydney Beaches (Warriewood to Manly) (M)	*Noctiluca scintillans*[4]
Jan-97	Evans Head and Coffs Harbour (M)	*Trichodesmium erythraeum*[4]
Jan-97	St Georges Basin and Jervis Bay (M)	*Noctiluca scintillans*[4]
Jan-97	Toowoon Bay and south to Bateau Bay (M)	*Noctiluca scintillans*[4]
Jan-97	Port Stephens (M)	*Noctiluca scintillans*[4]
Feb-97	Central Coast (M)	*Noctiluca scintillans*[4]
Feb-97	Jervis Bay (M)	*Noctiluca scintillans*[4]
Feb-97	Sydney Beaches (Collaroy to Coogee) (M)	*Noctiluca scintillans*[4]
Feb-97	Coledale to Astinmer (M)	*Noctiluca scintillans*[4]
Feb-97	Manly (Sydney) (M)	*Noctiluca scintillans*[4]

Feb-97	Warriewood (Sydney) (M)	*Noctiluca scintillans*[4]
Feb-97	Vincentia (Jervis Bay) (M)	*Noctiluca scintillans*[4]
Feb-97	Berowra Creek (Hawkesbury River) (E)	*Pseudonitzschia pungens*[4]
Apr-97	Frenchmans Bay (Botany Bay) (E)	*Noctiluca scintillans*[4]
Apr-97	Lake Macquarie (E)	*Noctiluca scintillans*[4]
Jul-97	Stockton Bight to Birubi Point (M)	*Anaulus australis*[4]
Aug-97	Bass Point (Sydney) (M)	*Noctiluca scintillans*[4]
Sep-97	St. George's Basin Beach (E)	*Noctiluca scintillans*[4]
Sep-97	Otford and Werrong (Royal National Park) (M)	*Noctiluca scintillans*[4]
Oct-97	Newcastle (M)	*Noctiluca scintillans*[4]
Dec-97	Illawarra Region (M)	*Noctiluca scintillans*[4]
Dec-97	Sydney northern beaches and Port Stephens (M)	*Noctiluca scintillans*[4]
Jan-98	Sydney northern beaches and Central Coast (M)	*Noctiluca scintillans*[4]
Jan-98	Boat Harbour to Boulder Bay (M)	*Trichodesmium erythraeum*[4]
Jan-98	Stanwell Park to Kiama (M)	*Noctiluca scintillans*[4]
Jan-98	Cronulla and Illawarra Region (M)	*Noctiluca scintillans*[4]
Jan-98	Batemans Bay (M)	*Noctiluca scintillans*[4]
Feb-98	Cronulla (M)	*Noctiluca scintillans*[4]
Feb-98	Clifton (Illawarra region) (M)	*Noctiluca scintillans*[4]
Feb-98	Whale Beach (Sydney) (M)	*Noctiluca scintillans*[4]
Feb-98	Collaroy Beach (Sydney) (M)	*Noctiluca scintillans*[4]
Mar-98	Sydney beaches and Bonnie Hill (Coffs Harbour) (M)	*Noctiluca scintillans*[4]
Mar-98	Coffs Harbour (M)	*Trichodesmium erythraeum*[4]
Mar-98	Evans Head (M)	*Trichodesmium erythraeum*[4]
Apr-98	Wollongong and Batemans Bay (M)	*Trichodesmium erythraeum*[4]
Apr-98	Richmond River (Ballina) (M)	*Trichodesmium erythraeum*[4]
May-98	Wallaga Lake (E)	*Noctiluca scintillans*[4]
Aug-98	St Georges Basin (E)	*Noctiluca scintillans*[4]
Sep-98	Lake Macquarie (E)	*Noctiluca scintillans*[4]
Sep-Oct-98	Gudgen Creek (Kingscliff, Grafton) (E)	*Trichodesmium erythraeum*[4]
Oct-98	Berowra Creek (Hawkesbury River) (E)	*Pseudo-nitzschia*[4] *pseudodelicatissima*[4]
Dec-98	Illawarra Region (Thirroul and Coalcliff) (M)	*Noctiluca scintillans*[4]
Dec-98	North Coast NSW (various reports) (M)	*Trichodesmium erythraeum*[4]
Dec-98	Lake Illawarra (E)	*Noctiluca scintillans*[4]
Jan-99	North Coast NSW (various reports) (M)	*Trichodesmium erythraeum*[4]
Mar-99	Offshore from Jervis Bay	*Trichodesmium erythraeum*[4]
Oct-99	Richmond River E	*Trichodesmium erythraeum*[4]
Nov-99	Lake Illawarra (E)	*Noctiluca scintillans*[4]
Nov/Dec-99	Seven Mile Beach (Gerringong) (M)	*Anaulus australis*[4]
Dec-99	Sydney northern beaches (M)	*Noctiluca scintillans*[4]

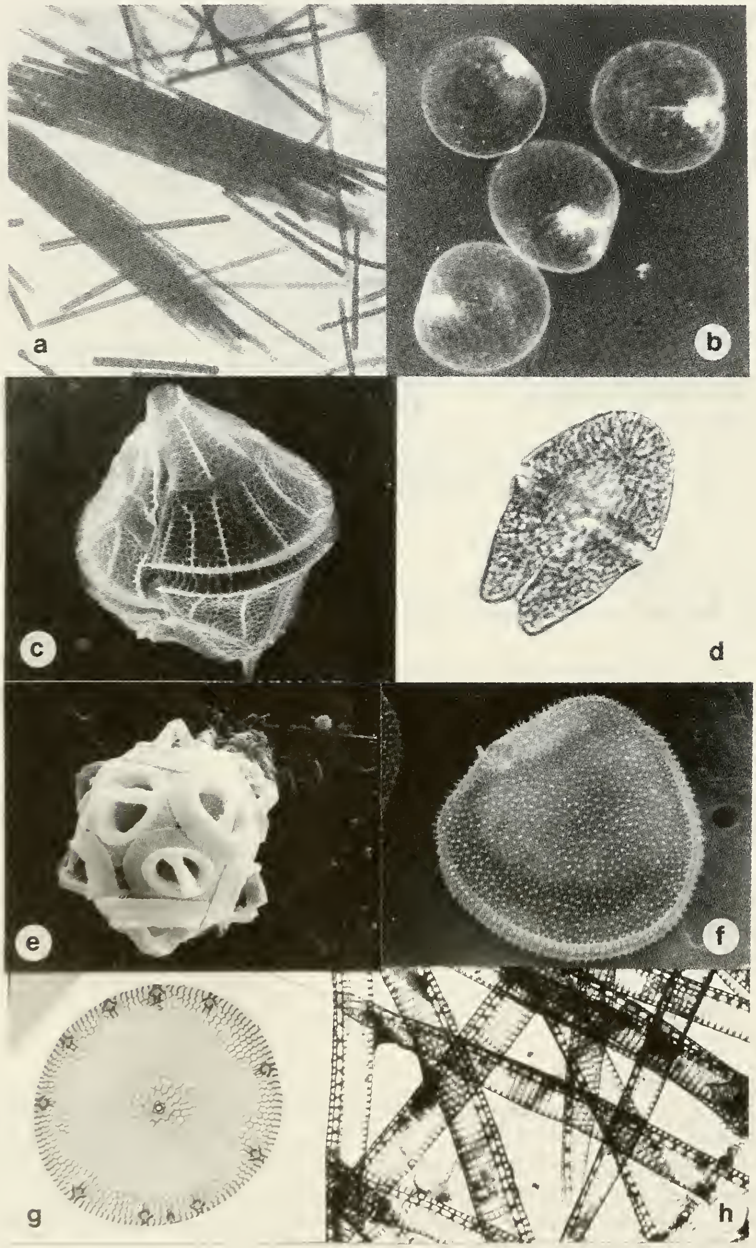
[1] Dakin and Colefax 1933, [2] Blackburn and Cresswell 1993, [3] Hallegraeff 1995, [4] EPA unpublished

RESULTS

Harmless Algal Blooms

The majority of visible algal blooms in NSW coastal waters have been harmless water discolourations (Table 1). Most of these blooms were of the large (200-800µm cell diameter) heterotrophic dinoflagellate *Noctiluca scintillans* 'Red tides' of this species have been reported in offshore, coastal and estuarine waters including coastal lagoons of NSW. The majority of blooms occurred in spring and summer and especially after heavy rainfall. Also the resultant high ammonia content released after cell lysis may irritate fish that will generally avoid the bloom area (Okaichi and Nishio 1976).

Figure 2a. LM. Filamentous cyanobacterium *Trichodesmium erythraeum* producing raft-like bundles, up to 750 μm long; b. LM. Balloon-shaped, colourless dinoflagellate *Noctiluca scintillans*, 200-500 μm diameter; c. SEM. Dinoflagellate *Gonyaulax polygramma*, showing ornamented cellulose plates with longitudinal ridges, cells 29-66 μm long; d. LM. Large, 50-80 μm long, unarmoured dinoflagellate *Gymnodinium sanguineum* ("sanguineum"=blood); e. SEM. Calcareous nanoplankton *Gephyrocapsa oceanica*, 15 μm diameter; f. SEM. Triangular, armoured dinoflagellate cells, 10-15 μm wide, of *Prorocentrum minimum*, covered with minute spinules; g. TEM. weakly silicified cell of the centric diatom *Thalassiosira partheneia*, 10 μm diameter; h. TEM. Pennate diatom bloom of *Pseudo-nitzschia pseudodelicatissima.* Cells 57 to 150 μm long.



N. scintillans (Fig. 2b) has long been present in NSW waters with its earliest record being related to its bioluminescent properties which were observed in Sydney Harbour by Bennett in 1860. In 1933 Dakin and Colefax referred to this species as a relatively minor component of the phytoplankton community in NSW coastal waters. Hallegraeff (1995) collated an historic overview of visible algal blooms in Australian waters with the first visible bloom of *N. scintillans* recorded in NSW waters in August 1982 (Lake Macquarie, central NSW). Since then, *N. scintillans* blooms appear to have increased in frequency and intensity (maximum cell density recorded as 5 x 10^4 cells/L in Jervis Bay February 1997). Over a one year sampling period from April 1997 to April 1998 at the CSIRO long-term coastal station off Port Hacking, Ajani et al. (1999) observed *N. scintillans* in 61% of samples and was absent from a very few samples in the autumn and winter months. The high frequency of occurrence for this species was unprecedented in these waters. This increase compared to earlier studies reinforces the need to investigate the global potential of *Noctiluca* as an indicator of coastal eutrophication (Porumb 1992; Qi et al. 1993; Lu et al. 1994; Huang and Qi 1997).

The cyanobacterium *Trichodesmium erythraeum* (Fig. 2a) is also a common 'red tide' organism in NSW coastal waters. This tropical/subtropical species produces episodic blooms that were historically reported as 'sea sawdust' during Captain Cook's voyage through the Coral Sea (Cribb 1969). The filaments of this alga are united into small bundles that are just visible to the naked eye (~1mm). Blooms are most commonly seen in northern NSW waters in spring, summer and early autumn when the East Australian Current (EAC) transports these algal masses into NSW from Queensland waters. These blooms can appear yellow-grey in their early stages, while later they become a reddish-brown. Recent reports (Hahn and Capra 1992; Endean et al. 1993) suggest that this alga can produce compounds with a mouse intraperitoneal potency but this requires further investigation.

Various *T. erythraeum* blooms have occurred in NSW waters with a particularly large bloom recorded on the south coast (Batemans Bay – south coast NSW) in early April 1998. Satellite imagery from NSW at his time showed unusually warm water throughout the NSW south coast area. This suggested that a strong manifestation of the EAC transported and conceivably triggered the extensive–*T. erythraeum* bloom in Batemans Bay (Clyde River estuary). The annual distribution of this species as reported by Ajani et al. (1999) from the Port Hacking 100m station also shows peak concentrations of this species in the coastal waters off Sydney in mid-April when surface waters were >~22°C.

Gymnodinium sanguineum (Fig. 2d), a large non-toxic dinoflagellate, has produced red water discolourations in NSW estuarine waters on several occasions (Hallegraeff 1991). Dakin and Colefax (1933) reported the first blooms in Sydney Harbour in July-August 1930, 1931 and 1932. Further blooms of this species have occurred in the Cooks River/ Alexandra Canal (Sydney) in October 1980, Lane Cove River in October 1981, Berowra Creek (a tributary of the Hawkesbury River estuary) in 1992 and 1994, and in North Harbour, Sydney in August 1995. This species has recently been renamed as *Akashiwo sanguinea* (Daugbjerg et al. 2000)

Another dinoflagellate that is common in the plankton of Australian waters is *Prorocentrum minimum* (Fig. 2f). This small ovate species can form extensive blooms and although it has been circumstantially linked with a shellfish-poisoning event in Norway in 1979 (venerupin poisoning), no toxic events have occurred in Australia to date (Hallegraeff 1991). In March 1995, this species bloomed in Berowra Creek. Each year this species becomes a dominant component of the phytoplankton in this reach of the Hawkesbury River. In offshore waters, maximum concentrations of this species have been observed in October (Ajani et al. 2001).

A rarely reported 'surf diatom', *Anaulus australis*, was reported as causing oily slicks along Stockton Beach to Birubi Point (Hunter region) in July 1997 and again in

November/December 1999 at Seven Mile Beach (Gerringong). These cells are able to rise to the surface and form dense accumulations by attaching themselves to wave-generated bubbles in high-energy surf zones. In most cases these accumulations disappear at night and reappear each morning. This species had only previously been reported along the southern coasts of South Africa and Australia (McLachlan and Hesp 1984; Campbell 1996).

Beginning in December 1992, the NSW coastal embayment of Jervis Bay was impacted for four weeks by an unprecedented, mono-specific bloom of the small (<10 μm) cosmopolitan coccolithophorid *Gephyrocapsa oceanica* (Fig. 2e). It has been proposed that the combination of upwelled cool nutrient-rich slope water and an influx of warm EAC waters, providing enhanced upper layer temperatures and an oceanic algal seed, was the initial mechanism causing the milky green bloom (Blackburn and Cresswell 1993). The maximum cell density of 2×10^7 cells/L (EPA unpublished) is greater than any previously recorded of this species in Australian waters.

Deep purple, red or muddy looking blooms of the ciliate protozoan *Mesodinium rubrum (=Myrionectra rubrum)* (Fig. 3d) are common in estuarine waters or sheltered embayments. These organisms contain cryptomonad algal symbionts. Blooms have usually been found to coincide with periods of warm and calm weather although no harmful effects have ever been recorded from such blooms (Bary 1953).

Potentially Harmful Algal Blooms – Species harmful to marine organisms

Some algal blooms can become so dense that they can cause death to fish and invertebrates due to either oxygen depletion or by abrasion damage to their gills (Table 2). A silicoflagellate *Dictyocha octonaria* (Fig. 3h) was implicated as the causative organism in a fish kill which occurred in coastal waters off Newcastle in February 1993. Dead fish (especially *Caranx* sp.) were seen on beaches between Burwood Beach and Redhead and floating up to 3km offshore. While silicoflagellates are regularly seen in these waters in the spring and summer months (Ajani et al. 2001), a bloom event of this magnitude had never previously been recorded in NSW waters (Hallegraeff 1991).

The non-toxic dinoflagellate *Gonyaulax polygramma* (Fig. 2c) also has the potential to develop harmful anoxic 'red tides'. Blooms in NSW have occurred in Sydney Harbour (Middle Head, July 1984), Darling Harbour (January 1993), Bate Bay (February 1993) and the most recent in Lake Macquarie in October 1993.

Both colony-forming diatoms, *Thalassiosira partheneia* (Fig. 2g) and *T. weissflogii,* have bloomed in NSW coastal waters. *T. partheneia* bloomed in NSW coastal waters from August to September 1985 and was the dominant bloom species encountered during weekly sampling at the Port Hacking 100m station (Ajani et al. 2001). *T. weissflogii* bloomed in the Alexandra Canal in February 1986. An unidentified species belonging to the genus *Thalassiosira* bloomed at three locations in the Hawkesbury River in March 1999 - Berowra Creek (3×10^6 cells/L), Calabash Bay (3×10^6 cell/L) and Neverfail (5×10^5 cell/L). Despite oyster leases being nearby, no economic loss was reported from these blooms. In Tokyo Bay in 1951 a similar species, *T. mala*, bloomed and damaged the gills of cultured bivalves resulting in significant economic loss (Takano 1956).

Red-brown blooms of the dinoflagellate, *Scrippsiella trochoidea* (Fig. 3a), have been reported in NSW coastal waters as early as the 1890s (Whitelegge 1891). This species has also caused water discolourations in the Hawkesbury River in March 1991 and Jervis Bay in 1994. Although non-toxic, this commonly occurring species can cause deoxygenation of the water and subsequent fish kills when it blooms in sheltered bays (Hallegraeff 1991).

A bloom of *Chaetoceros* spp. occurred in January 1998 in Gunnamatta Bay, Port Hacking. No harmful effects were observed from this bloom, however large concentrations of some *Chaetoceros* spp. can potentially damage the gills of fish, which in turn produce mucus that induces hypoxia (oxygen deficiency in the body's tissues) and hypercapnia (excessive amount of carbon dioxide to the blood) (Rensel 1993). The estuarine bloom coincided with maximum cell densities of this genus at the long-term station offshore from Port Hacking (Ajani et al. 2001).

Figure 3a. SEM. Red-water dinoflagellate *Scrippsiella trochoidea*, 16-36 µm long. Note tube-shaped apical pore on top of the cell and nearly equatorial (not displaced) girdle groove; b. LM. Chain-forming dinoflagellate *Alexandrium catenella*, causative organism of paralytic shellfish poisoning. Individual cells 20-22 µm long.; c.SEM. Red water dinoflagellate *Alexandrium minutum*, causative organism of paralytic shellfish poisoning. Individual cells 24-29 µm diameter. Note the hook-shaped apical pore on top of the cell and characteristic shape of the connecting first apical plate.; d. LM. Ciliate *Mesodinium rubrum*, 30 µm diameter, with two systems of cilia arising from the waist region.; e. LM."Raspberry"-like cell of the fish-killing flagellate *Heterosigma akashiwo* ("akashiwo"=red tide), containing numerous disc-shaped chloroplasts. Cell 11-25 µm long.; f.LM. Undescribed flagellate resembling *Haramonas*. The cell surface is covered by numerous mucous-producing vesicles. Cells 30-40 µm long. ; g. SEM. Small armoured dinoflagellate *Dinophysis acuminata*, causative organism of diarrhetic shellfish poisoning. Cells 38-58 µm long.; h. SEM. Siliceous skeleton of the silicoflagellate *Dictyocha octonaria*, 10-20 µm diameter; i. SEM. Small unarmoured, fish-killing dinoflagellate *Gymnodinium galatheanum*, 15 µm diameter.

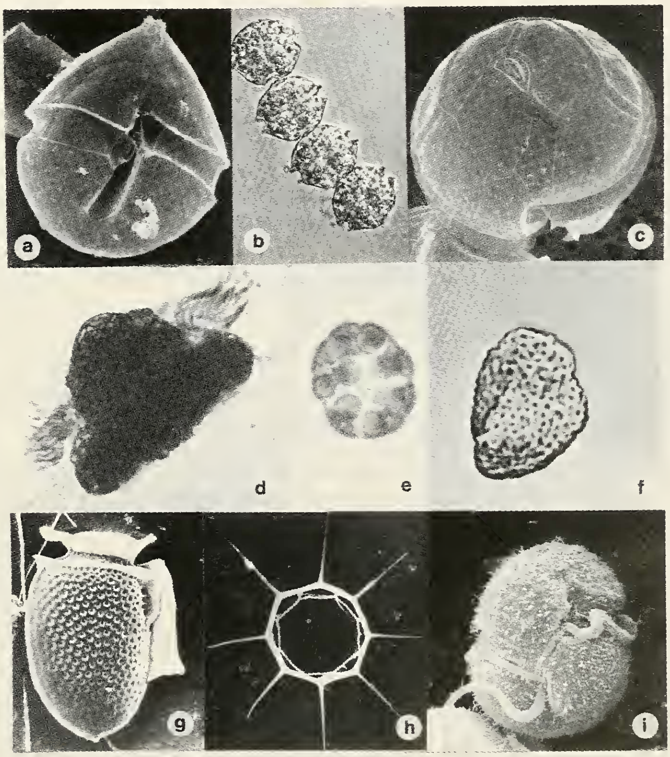


Table 2. Algal blooms recorded in New South Wales's marine (M) and estuarine (E) waters - potentially harmful to marine organisms

Date	Location	Bloom Taxa
1890	Sydney Harbour (E)	*Scrippsiella trochoidea*[1]
July-84	Middle Head, Sydney Harbour (E)	*Gonyaulax polygramma*[2]
Aug- 85	NSW Coast (M)	*Thalassiosira partheneia*[3]
Feb-86	Alexandra Canal (Cooks River, Sydney) (E)	*Thalassiosira weissflogii*[4]
Mar-91	Hawkesbury River (E)	*Scrippsiella trochoidea*[4]
Jan-93	Darling Harbour (Sydney) (E)	*Gonyaulax polygramma*[4]
Feb-93	Burwood Beach to Redhead(Newcastle) (M)	*Dictyocha octonaria*[4]
Feb-93	Bate Bay (M)	*Gonyaulax polygramma*[4]
Oct-93	Lake Macquarie (E)	*Gonyaulax* sp[5]
Mar-95	Lake Illawarra (E)	*Gymnodinium* cf. *mikimotoi*[5]
Jan-98	Gunnamatta Bay (Port Hacking, Sydney) (E)	*Chaetoceros* spp[5]
Mar-99	Berowra Creek, Calabash Bay and Neverfail (Hawkesbury River) (E)	*Thalassiosira* sp[5]
Dec -99	Kianga Lake, NSW South coast (E)	*Chaetoceros spp.*[5]

[1] Whitelegge 1890, [2] SPCC unpublished, [3] Hallegraeff 1991, [4] Hallegraeff 1995, [5] EPA unpublished

Potentially Harmful Algal Blooms - Toxic species

Various algal species are potentially toxic to fish and humans (Fig. 3 and Table 3). *Heterosigma akashiwo (= H. carterae*) (Fig. 3e) a toxic raphidophyte, bloomed in Salamander Bay, Port Stephens (1980), Berowra Creek (November 1991, July 1995) and Sydney Harbour (November and December 1995). These potato-shaped cells contain numerous ejectosomes that readily discharge (especially upon preservation) making microscopic identification difficult. The toxicity of this species to fish was illustrated in the Puget Sound (USA) area where fish kills resulted in a considerable monetary loss to the salmonoid aquaculture industry (Rensel et al. 1989). The toxic mechanism of this species is still under investigation although data suggest that it is through the disruption of the fish gill lamellae. Hypotheses for this toxicity include possible production of high concentrations of superoxide radicals (Yang et al. 1995), the presence of heterotrophic bacteria which may explain the cell's high toxin variability (Carrasquero-Verde 1999), or the presence of a neurotoxin which is similar to, but not identical to, brevetoxin (Kahn et al 1998)

Another toxic raphidophyte, *Chattonella* cf. *globosa*, bloomed sporadically in Canada Bay, Sydney Harbour, from November 1996 to March 1997. Blooms of related species have caused significant mortality of cultured yellowtail and red sea bream in Japanese inland seas (Okaichi 1985) and implicated in the mass mortality of farmed bluefin tuna in Boston Bay, South Australia in 1996 (Marshall and Hallegraeff 1999). The production of superoxide radicals as the major mechanism of fish mortality is also hypothesised for this genus. Evidence for brevetoxin-like production is still being investigated.

A raphidophyte flagellate, *Haramonas dimorpha* was identified and described from the mouth of the Daintree River, northeast Australia by Horiguchi in 1996. This genus is distinguished from other raphidophytes by the cell shape, the possession of a tubular invagination and a unique arrangement of chloroplasts. In December 1998, a closely related but as yet undescribed *Haramonas* species (Fig. 3f), was implicated in a fish kill in Morrisons Bay, Parramatta River. Rainfall and proximity to a major stormwater canal were possibly contributing factors to bloom development in these waters.

Another microalga associated with toxicity to fish is *Gymnodinium galatheanum* (Fig. 3i). Between June and July 1991 this species was implicated in two extensive fish

Table 3. Algal blooms recorded in New South Wales's marine (M) and estuarine (E) waters - potentially toxic to humans

Date	*Location*	*Bloom Taxa*
Feb-45	Port Hacking (M)	*Alexandrium catenella*[1]
1980	Salamander Bay (Port Stephens) (E)	*Heterosigma akashiwo*[2]
Jun-91	Lake Illawarra (E)	*Gymnodinium galatheanum*[2]
Nov-91	Berowra Creek (Hawkesbury River) (E)	*Heterosigma akashiwo*[2]
Sep-93	Newcastle Harbour (E)	*Alexandrium catenella*[3]
Oct-93	Parramatta River (Sydney) (E)	*Alexandrium catenella*[3]
Nov-93	Berowra Creek (Hawkesbury River) (E)	*Pseudonitzschia multiseries*[3]
Jan-94	Berowra Creek (Hawkesbury River) (E)	*Gymnodinium galatheanum*[3]
Mar-94	Jervis Bay (M)	*Prorocentrum* sp, *Dinophysis* sp *and Ceratium furca*[3]
Jan-95	Berowra Creek (Hawkesbury River) (E)	*Pseudonitzschia multiseries*[3]
Mar-95	Berowra Creek (Hawkesbury River) (E)	*Gymnodinium* sp.[3]
Jul-95	Berowra Creek (Hawkesbury River) (E)	*Heterosigma akashiwo*[3]
Nov and Dec-95	Sydney Harbour (E)	*Heterosigma akashiwo*[3]
Nov-96-	Parramatta River (Sydney Harbour) (E)	*Chattonella globosa*[3]
Mar-97	Ballina (M)	*Dinophysis acuminata*[3]
Dec-1997 Mar-1998	Stockton Beach (M)	*Dinophysis acuminata*[3]
Dec-98	Morrisons Bay (Parramatta River) (E)	*Haramonas* sp. nov.[3]
Apr 99- Mar 2000	The Broadwater (Myall Lakes) (E)	*Microcystis aeruginosa*[3,4]
Oct-99	Wagonga Inlet, Narooma (E)	*Pseudonitzschia* spp.[4]
Nov-99	Parramatta River (Sydney Harbour) (E)	*Alexandrium* sp.[3]

[1] Hallegraeff 1995, [2] SPCC unpublished, [3] EPA unpublished, [4] AWT unpublished

kills in Lake Illawarra. Berowra Creek also experienced a bloom of this species in early 1994. *G. galatheanum* has been reported to produce toxins that are lethal to the eggs and larvae of certain fish. It is believed that the toxin produced is a haemolytic toxin, which affects the permeability of red blood cells. The physiological response of fish organisms to the toxin is believed to be the damage and necrosis of gill filament epithelial cells (Nielsen 1993). This species has recently been renamed as *Karlodinium micrum* (Daugbjerg et al. 2000).

Dinophysis acuminata (Fig. 3g) and *D. tripos*, both producers of diarrhetic shellfish poisoning (DSP), were implicated in the contamination of edible bivalves (*Donax sp.*) at Ballina, approximately 700 km north of Sydney, in December 1997 and in the Hunter area, approximately 200 km north of Sydney, in March 1998. Fifty-nine cases of gastroenteritis in humans were reported from Ballina and 23 cases were reported from the Hunter area following consumption of the bivalve. A mouse bioassay revealed a positive result for an unidentified DSP toxin and both species were found in the gut of the bivalve. Pectenotoxin DSP toxins have now been fully characterised (Quilliam et al., 2000). Peak concentrations of *D. acuminata* at the Port Hacking 100m station occurred in January (Ajani et al. 2001).

Species belonging to the genus *Pseudo-nitzschia* have been implicated as the causative organisms of amnesic shellfish poisoning (UNESCO 1995; Hallegraeff 1994). Blooms of the toxic species *P. multiseries* were detected in Berowra Creek in 1993 and 1995 (5% of total phytoplankton biomass, EPA unpublished)(Table 3). A bloom predominantly of *P. pseudodelicatissima* (Fig. 2h) was detected in Berowra Creek from October to November 1998. Although this species has been found to be toxic elsewhere

(UNESCO 1995), analysis results from oysters from nearby leases showed no detectable concentrations of domoic acid, In October 1999, oyster leases in Wagonga Inlet, Narooma, were closed for harvesting due to a bloom of *P. pseudodelicatissima, P. pungens* and *P. australis* (toxic species) (Lapworth et al. 2000) (Table 3). *P. pungens,* a harmless species, also bloomed in Berowra Creek in July 1994 and again in February 1997 (Table 1).

Many species of this genus have been observed at the 100m Port Hacking station (Hallegraeff and Reid 1986; Ajani et al. 2001). Scanning electron microscopy of samples collected from this station during 1997-1998 identified two potentially toxic species, *P. australis* and *P. multiseries* as well as the harmless species *P. pseudodelicatissima, P.* cf. *subfraudulenta, P. pungens, P. subpacifica* and *P. heimii* (Ajani et al. 2001).

Two species of the dinoflagellate genus *Alexandrium* have been found to produce Paralytic Shellfish Poisoning (PSP) in NSW coastal waters - *Alexandrium catenella* (Fig. 3b) and *Alexandrium minutum* (de Salas et al. 2000). *A. catenella* is thought to be the causative organism for the first record in Australian medical literature of human shellfish poisoning. This account is of wild mussels collected in February 1935 near Batemans Bay that produced typical PSP symptoms in mice (Le Messurier 1935). Since then, blooms of *A. catenella* have occurred in Port Hacking (1945) and in the Parramatta River in October 1993 (maximum cell count 9.5×10^3 cells/L, EPA unpublished). Samples of wild oysters collected during this time were found to contain more than 3 mg/kg of saxitoxin, which exceeded the statutory limit for Paralytic Shellfish Poisoning toxin concentrations of 0.8 mg/kg, prescribed under the NSW Food Act, 1989. Low levels of this toxin were also detected in harbour prawns. This species also bloomed in Newcastle harbour in September 1993.

Toxic cysts (non-motile resting stage of some species) have been found in many NSW coastal estuaries and embayments. Cysts of *Alexandrium* have been reported in the gut of oysters from Port Stephens, a major NSW shellfish growing area (Richardson 1991). Sediment samples from oyster growing areas in Botany Bay in 1993 also contained resting cysts of the potentially toxic dinoflagellate genus *Alexandrium* (Lincoln-Smith and Smith 1993). It is unknown if these cysts were from potentially toxic species.

A cyst survey of surface sediments in 1995 revealed the widespread occurrence of the toxigenic dinoflagellate *Alexandrium catenella* in the Lower Hawkesbury River, Sydney Harbour, Woolooware Bay, Botany Bay, and Port Hacking to Batemans Bay (Hallegraeff et al 1995). These results confirm Hallegraeff's previous finding of this species at Batemans Bay in 1991. Cysts of'*A. catenella* were also found at low concentrations in surface sediments taken from several sites in Twofold Bay as part of an introduced marine pest survey in the Port of Eden by CRIMP (Centre for Research into Introduced Marine Pests) (1997). In 1992 Hallegraeff and Bolch examined the ballast water from a vessel which had its ballast tanks filled during a toxic dinoflagellate bloom in Japan. An estimated >300 million viable *Alexandrium* cysts were contained in this vessel upon arriving at the Port of Eden. This indicated that both diatoms and dinoflagellates that are not endemic to a region could be inadvertently introduced when their resistant resting stages are discharged with ballast-tank waters and the sediments of bulk cargo vessels.

A. catenella and *A. minutum* (Fig. 3c) have recently been detected in the Port of Newcastle during a similar survey (CRIMP 1999). Plankton samples during this survey also showed high numbers of vegetative cells of *A. catenella* in the water column, indicating that early spring might be a potential bloom period for this species. In addition, large numbers of *A. minutum* cysts were found at a dredge disposal site offshore from Newcastle. The most northern report of these species in New South Wales to date is Newcastle.

In March 1994, a bloom of three dominant dinoflagellate taxa occurred in Jervis Bay: *Prorocentrum* sp, *Dinophysis* sp and *Ceratium furca (*EPA unpublished). There is no information available on maximum cell count, bloom colour, extent or duration.

Species of the toxic cyanobacteria genera *Anabaena* and *Microcystis* are freshwater species that sometimes bloom in brackish/marine waters. Throughout 1999 and early 2000, *Anabaena circinalis* bloomed along the shoreline of the Myall Lakes, central NSW. *Mircocystis aeruginosa* increased in numbers towards the end of the bloom and low levels of toxins were detected in samples taken in early February 2000.

Table 4. Unidentified algal blooms recorded in New South Wales's marine (M) and estuarine (E) waters

Date	*Location*	*Bloom Taxa*
Nov-94	Taree (M)	Unidentified Species[1]
Dec-95	North Bridge (Sydney Harbour) (E)	Unidentified Species[1]
Mar-96	Evans Head (M)	Unidentified Species[1]
Apr-96	Seal Rocks (M)	Unidentified Species[1]
Aug-96	Maroubra Beach (Sydney) (M)	Unidentified Species[1]
Dec-96	Sydney Harbour (E)	Unidentified Species[1]
Oct-97	Brunswick Headland (M)	Unidentified Species[1]
Jan-98	Sydney northern beaches (M)	Unidentified Species[1]
Jan-98	Iron Cove Bay (Sydney Harbour) (E)	Unidentified Species[1]
Jna-98	North Head (Sydney Harbour) (M)	Unidentified Species[1]
Mar-98	Sydney northern beaches (M)	Unidentified Species[1]
Dec-98	Sydney northern beaches (M)	Unidentified Species[1]
Feb-99	Warriewood Beach (Sydney) (M)	Unidentified Species[1]
May-99	Dee Why Beach (M)	Unidentified Species[1]
Sep-99	Baragoot Lake, Bega (E)	Unidentified Species[1]
Dec-99	Five Dock, Sydney (E)	Unidentified Species[1]

[1]EPA unpublished

Unidentified Blooms

In addition to the blooms discussed above there have been a number of reports where algal blooms were observed for which no species identifications were reported/ recorded (Table 4).

Reports of other toxic algae present in the plankton

There are many species of the dinoflagellate genus

Gymnodinium, of at least which ten are found in NSW coastal waters. Three species of this genus (*G. catenatum, G. breve and G. mikimotoi*) have been linked to toxic episodes elsewhere (PSP and NSP). There have been limited observations of these species in NSW coastal waters. A very localised cyst population of *G. catenatum* was found in Cowan Creek in 1995 (EPA unpublished). In 1998, this species was observed in the plankton from Calabash Bay, Berowra Creek. This was the first record of this species in the plankton of the Hawkesbury River.

The dinoflagellate *Alexandrium minutum* has been identified in the Shoalhaven River in 1993 but to date has not bloomed in NSW waters. The presence of cysts of this species in sediments from New South Wales waters has been discussed above.

During the recent sampling at the CSIRO long-term station off Port Hacking, other potentially harmful species were observed (Ajani et al. 2001). *Dinophysis tripos* was observed in 27% of samples collected throughout the year, *D. fortii* was present in 6% of samples and *D. acuta* 2%. *D. caudata* was also observed as 'present' in samples. These have all been implicated in diarrhetic shellfish poisoning (DSP) events throughout the world although toxin production is variable.

Figure 4a. Recorded algal blooms in NSW marine and estuarine waters (1970 - present) with human population data.

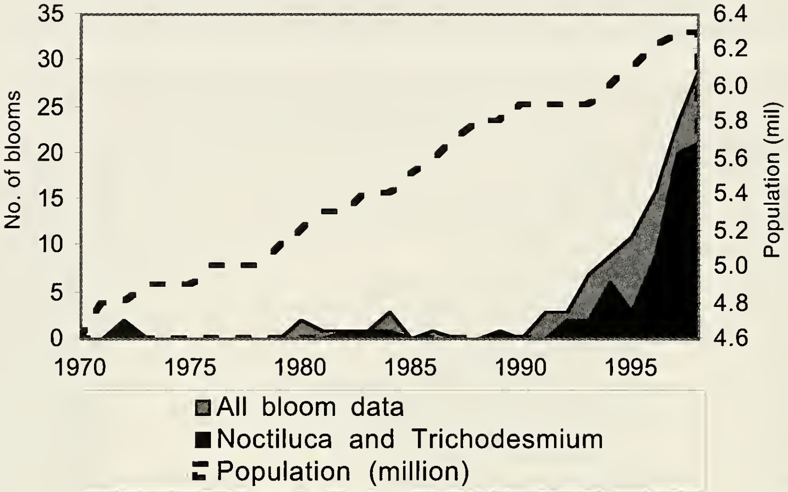
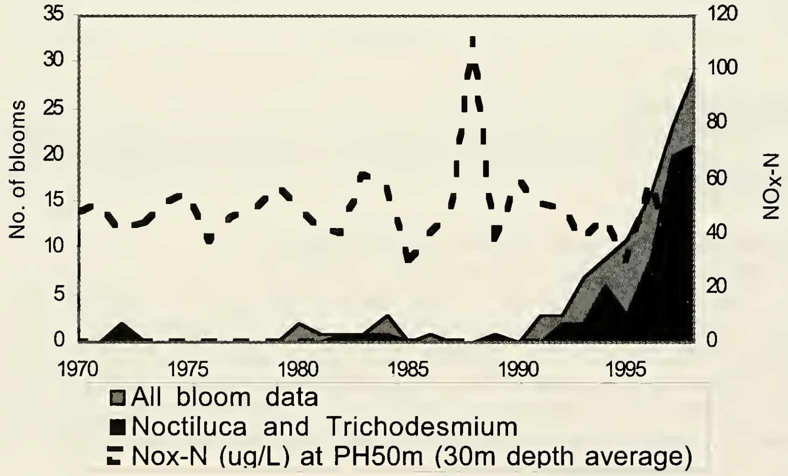


Figure 4b. Recorded algal blooms in NSW marine and estuarine waters (1970 - present) with annually averaged oxidised nitrogen concentrations.



DISCUSSION

This paper presents mainly *ad hoc* reports of bloom events in NSW marine and estuarine waters (Tables 1 to 4). It is likely that additional blooms have occurred and gone unreported. Bias in the data is therefore likely. The magnitude of this bias, and how significant the apparent changes in bloom reporting frequencies, are discussed below.

Factors favouring higher reporting rates include increased awareness of environmental issues especially water quality, increased reliance on fisheries resources for food production, coastal population growth (including the commissioning of new ocean outfalls), public awareness of research activities and the utilisation of our coastal fringes for recreational and aquaculture purposes. It is not surprising therefore, that algal bloom reports have increased dramatically since the early 1900s (Fig. 4).

Although warm, calm weather and the presence of nutrient rich slope water during summer months increases the probability of visible blooms, high reporting rates from December to March may also be associated with an increased population of opportunistic recreational observers (Fig. 5). In addition to this, the population of New South Wales has increased at a steady rate since 1970, reaching 6.3 million in 1998 (Fig. 4a)(Bray 1995-1999).

The diversion of sewage effluent in Sydney from shoreline outfalls to deepwater outfalls in 1990 may have affected phytoplankton populations although intrusions of nutrient-rich slope water have been identified as the principal factor leading to the development of marine algal blooms in these waters (Pritchard et al. 1999).

Nutrient concentrations in NSW coastal waters vary considerably over time. Long-term trends in CSIRO data suggest possible increases in phosphate concentrations, (although phosphate data ceased to be collected in 1985). The nutrient ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus (DIN: DIP), and dissolved inorganic silicate to dissolved inorganic phosphorus (DIS: DIP) calculated from this long-term data set, however, show no clear trend to date. Annually averaged oxidised nitrogen concentrations from the CSIRO 50m long-term coastal station are shown in Fig. 4b. No clear pattern over time is evident. There were only four samples collected in 1988 and the low sampling frequency is believed to be the reason for the unusual peak in the annual average at this time. When the geographical distribution of blooms in NSW is examined, blooms are concentrated around major cities (Fig. 6). This is likely due to a combination of the larger communities available for *ad hoc* observations and reporting and higher anthropogenic inputs.

Figure 5. Annual distribution of recorded algal blooms in NSW marine and estuarine waters.

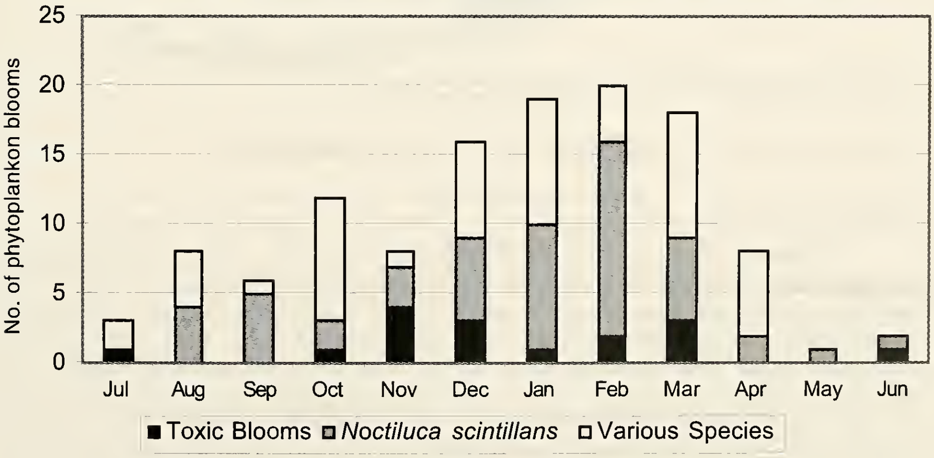
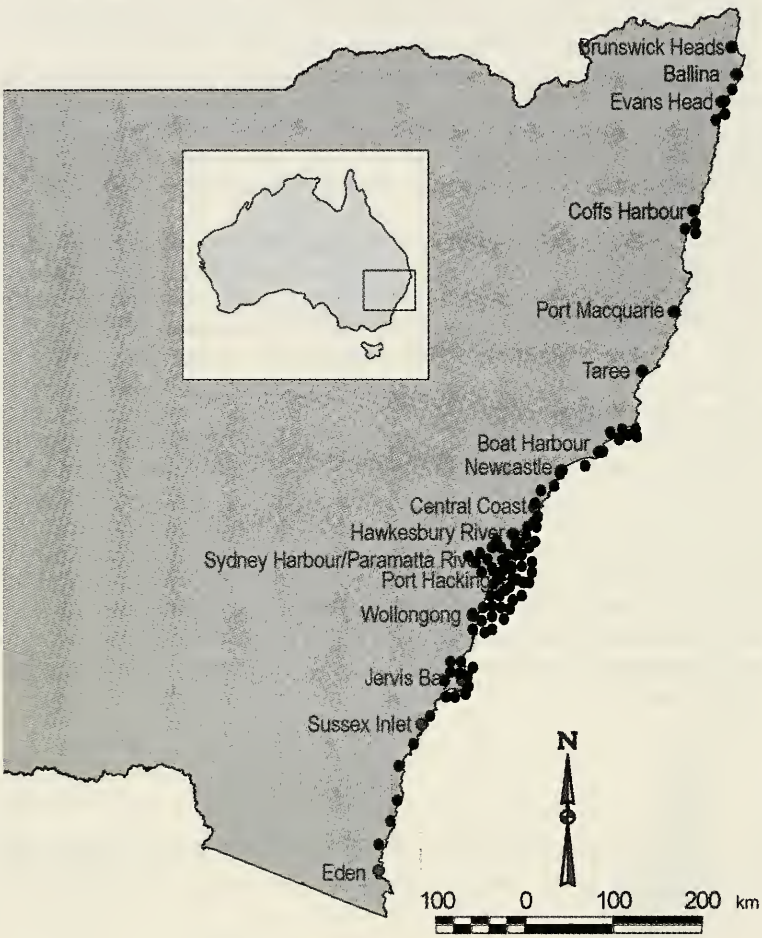


Figure 6, Geographical distribution of blooms in NSW marine and estuarine waters



Likewise, changes in the reporting and recording of algal blooms can introduce bias especially when most data come from *ad hoc* reports. For example, the EPA's ocean nutrient and phytoplankton project solicited and facilitated reporting and recording of blooms from 1995 to 1998 (between Port Stephens and Jervis Bay) and inevitably contributed to the high reporting frequencies at these locations and during these years. Extensive *Noctiluca scintillans* blooms observed off Sydney and Port Kembla during January-February 1993 were recorded as a single bloom event while during January-February 1997, 11 individual reports of *Noctiluca scintillans* blooms were recorded (Table 1). There is evidence to suggest that many of the 1997 blooms were associated with a regional dynamic that caused three to four broad scale slope water intrusion 'events'

Figure 7a. Algal secies distribution for recorded blooms in NSW marine and estuarine waters

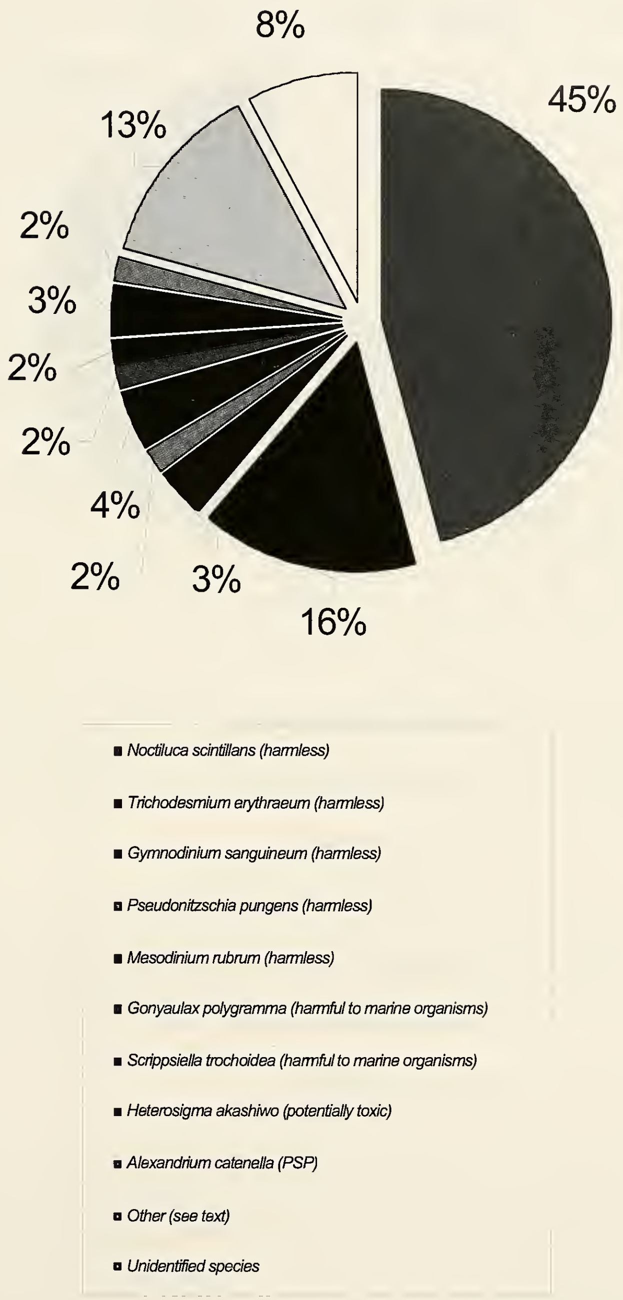
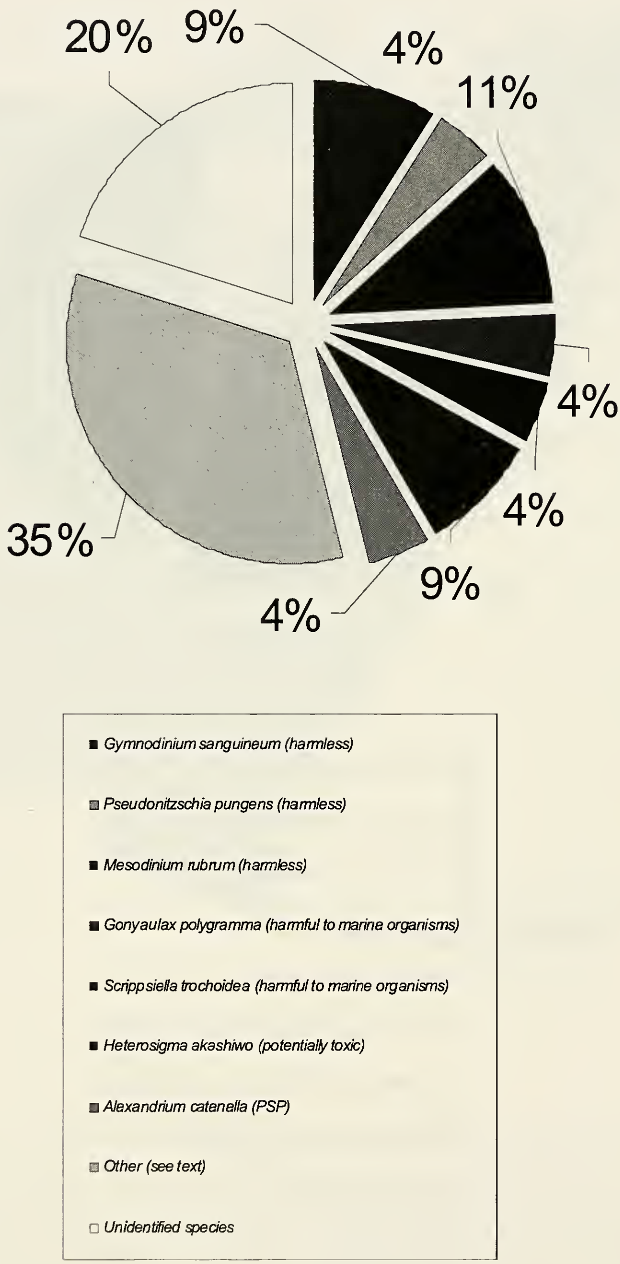


Figure 7b. Algal species distribution for recorded blooms in NSW estuarine waters only.



(Pritchard et al. 1997). In contrast, after the completion of data gathering for the ocean nutrient project, only 4 blooms were identified during the summer of 1998-99 and three of these were' *Trichodesmium erythraeum* that has a tropical and sub tropical origin and is readily identifiable. When *Noctiluca* and *Trichodesmium* blooms are removed altogether from the bloom reports, the remaining reported blooms are predominantly estuarine blooms (Figs 7a and 7b).

Water discolouration is also an important factor in the reporting of algal proliferations. Green algal blooms blend somewhat with the naturally changing spectra of coastal waters, and therefore are likely to go unreported. The more prominent bloom colours such as yellow, brown, red or milky (Hallegraeff 1991) are more 'visible' discolourations, and are therefore more likely to be noticed and recorded. Some species show no water discolouration but can be highly toxic at very low cell concentrations (Anderson 1995). In addition to this, many groups of algae remain poorly studied and it is likely that many more species will be found to bloom and more found to be toxic (Moestrup 1994).

These *ad hoc* data sets, therefore, generally promote hypotheses and speculation about changes and differences in bloom events rather than providing the data set to test such hypotheses. Recognition of the limitations of the existing data emphasises the need to adopt more consistent monitoring/surveillance and recording protocols. Despite potential bias associated with *ad hoc* reports of visible blooms, there appears to be a compelling argument, supported by quantitative data (e.g. Hallegraeff and Reid 1986 and Ajani et al. 2001), to suggest that visible blooms in recent years have become dominated by *Noctiluca scintillans* with evidence to suggest that this was not the case two decades ago. In fact, forty-five percent of all recorded blooms in these waters were caused by the dinoflagellate *Noctiluca scintillans* (Fig. 7a). Causal factors for this dominance remain unclear although large scale phenomena such as the El Nino Southern Oscillation may be a significant factor contributing to long term variability (Lee et al. 2001). (The 'other' group in these Figs 7a and 7b consists of novel bloom species, i.e. species that have been recorded as blooming only once to date).

Long term data collection on phytoplankton populations and algal bloom events in NSW waters, and the use of emerging technologies such as molecular probes, remote sensing and physical/chemical/biological modelling, could be invaluable in the understanding of phytoplankton dynamics and their role in ecosystem health.

ACKNOWLEDGMENTS

The authors would like to thank EPA staff Mr Randall Lee, Mr Paul Rendell, Mr Sean Hardiman and Mr Kieran Horkan for their contributions. We are also grateful to Dr Peter Scanes and Dr Tony Church for reviewing this manuscript. Additional taxonomic assistance was provided by Prof. Ojvind Moestrup (Dept. of Phycology, University of Copenhagen, Denmark), Dr Steve Brett (Microalgal Services, Victoria) and Ms Caroline Lapworth (University of Tasmania).

REFERENCES

Ajani, P., Lee, R., Pritchard, T. and Krogh, M. (2001). Phytoplankton dynamics at a long-term coastal station off Sydney, Australia. *Journal of Coastal Research (in prep.).*

Anderson, D.M. (1995). Toxic red tides and harmful algal blooms: a practical challenge in coastal oceanography. Rev. Geophysics, Suppl. U. S. National Report to the Int. Union of Geodesy and Geophysics. 1991-1994. pp. 1189-1200.

Bary, B.M. (1953). Sea-water discoloration by living organisms. *New Zealand Journal of Science and Technology*. March 1953: 393-407.

Bennett, G. (1860). 'Gatherings of a naturalist in Australasia: being observations principally on the animal and vegetable productions of New South Wales, New Zealand and some of the Austral islands'. (London: John Van Voorst, Paternoster Row).

Blackburn, S.I. and Cresswell, G. (1993). A coccolithophorid bloom in Jervis Bay. *Australian Journal of Marine and Freshwater Research* **44**, 253-260.

Bray, G. (1995-1999). 'New South Wales Year Book No.s 75-79'. Australian Bureau of Statistics, NSW.

Campbell, E.E. (1996). The global distribution of surf diatom accumulations. *Rev. Chil. Hist. Nat.* **69**, 495-450.

Carrasquero-Verde, J.R. (1999). Role of associated bacteria in *Heterosigma carterae* toxicity to salmonoids. *Aquatic. Toxicology* **45**, 19-34.

Cribb, A.B. (1969). Sea sawdust. *Queensland Naturalist* **19**, 115-117.

CRIMP (1997). 'Introduced species survey: Port of Eden and Twofold Bay, New South Wales'. CSIRO Centre for Research on Introduced Marine Pests.

CRIMP (1999). 'Introduced species survey: Newcastle, New South Wales'. CSIRO Centre for Research on Introduced Marine Pests.

Dakin, W.J. and Colefax, A. (1933). The marine plankton of the coastal waters of New South Wales. 1. The chief planktonic forms and their seasonal distribution.'*Proceedings Linnean Society N.S.W.* **58**, 186-222.

Dakin, W.J. and Colefax, A. (1940). The plankton of the Australian coastal waters off New South Wales. *University of Sydney Monograph No.1* (Australasian Medical Publishing Co: Sydney).

de Salas, M.F., van Emmerik, M.J., Bolch, C.J., Negri, A. and Hallegraeff, G.M. (2000). Genetic affinities of the Australian PSP dinoflagellates *Alexandrium catenella*, *A.tamarense* and *A.minutum*: introduced or indigenous? In 'Harmful Algal Blooms 2000' (Eds G.M. Hallegraeff, S.I. Blackburn, C.J. Bolch and R.J. Lewis). Proceedings of 9th International Conference on Harmful Algal Blooms. IOC. Paris.

Daugbjerg, N., G. Hansen, J. Larson and O. Moestrup. (2000). Phylogeny of some of the major genera of dinoflagellates based on ultrastructure and partial LSU rDNA sequence data including the erection of three new genera of unarmoured dinoflagellates. *Phycologia* **39**, 302-317.

Endean, R., Monks, S.A., Griffith, J.K. and Llewellyn, L.E. (1993). Apparent relationships between toxins elaborated by the cyanobacterium *Trichodesmium erythraeum* and those present in the flesh of the narrow-barred Spanish mackerel *Scomberomorus commersoni. Toxicology* **31**, 1155-1165.

EPA (1995). 'NSW State of the Environment 1995'. NSW Environment Protection Authority, Sydney.

Graneli, E. and Moreira, M.O. (1990). Effects of river water of different origin on the growth of marine dinoflagellates and diatoms in laboratory cultures. *Journal of Experimental Marine Biology and Ecology* **136**, 89-106.

Hahn, S.T. and Capra, M.F. (1992). The cyanobacterium *Oscillatoria erythraea*- a potential source of toxin in the ciguatera food-chain. *Food Additives and Contaminants*. **9**, 351-355.

Hallegraeff, G.M (1991). 'Aquaculturists guide to harmful Australian microalgae'. Fishing Industry Training Board of Tasmania/CSIRO. Division of Fisheries, Hobart.

Hallegraeff, G.M. (1992). Harmful algal blooms in the Australian region.'*Marine Pollution Bulletin*. **25**, 186-190.

Hallegraeff, G.M. (1993). A review of harmful algal blooms and their apparent global increase. *Phycologia*. **32**, 79-99.

Hallegraeff, G.M. (1994). Species of the diatom genus *Pseudonitzschia* in Australian Waters. *Botanica Marina* **37**, 397-411.

Hallegraeff, G.M. (1995). Algal blooms in Australian waters. *Water*, July/August: 19-23.

Hallegraeff, G.M. and Reid, D.D. (1986). Phytoplankton species successions and their hydrological environment at a coastal station off Sydney. *Australian Journal of Marine and Freshwater Research* **37**, 361-377.

Hallegraeff, G.M., Bolch, C.J., Blackburn, S.L. and Oshima, Y. (1991). Species of the Toxigenic dinoflagellate genus Alexandrium in southeastern Australian waters. *Botanica Marina* **34**, 575-587.

Hallegraeff, G.M. and Bolch, C.J. (1992). Transport of diatom and dinoflagellate resting spores in ships' ballast water: implications for plankton biogeography and aquaculture. *Journal of Plankton Research* **14**, 1067-1084.

Horiguchi, T. (1996). *Haramonas dimorpha* gen. et sp. nov. (Raphidophyceae), a new marine raphidophyte from Australian mangrove. *Phycological Research* **44**, 143-150.

Huang, C. and Qi, Y. (1997). The abundance cycle and influence factors on red tide phenomena of *Noctiluca scintillans* (Dinophyceae) in Dapeng Bay, the South China Sea. *Journal of Plankton Research* **19**, 303-318.

Jeffrey, S.W. and Hallegraeff, G.M. (1990). Phytoplankton ecology of Australasian waters. In: 'Biology of Marine Plants' (Eds Clayton, M. N., King, R. J. pp. 310-348. (Longman Cheshire: Melbourne).

Kahn, S., Arakawa, O. and Onoue, Y. (1998). Physiological investigations of a neurotoxin-producing phytoflagellate, *Chattonella marina* (Raphidophyceae). *Aquaculture Research* **29**, 9-17.

Lapworth, C.J., Hallegraeff, G.M. and Ajani, P.A. (2000) Identification of domoic-acid producing *Pseudo-nitzchia* species in Australian waters. 9th Int. Conf. Harmful Algal Blooms, Abstracts, p.159.

Lee, R., Ajani, P., Krogh, M. and Pritchard, T.R. (2001). Resolving climatic variance in the context of retrospective phytoplankton pattern investigations off the east coast of Australia. *Journal of Coastal Research* (in press).

Le Messurier, D.J. (1935). A survey of mussels on a portion of the Australian coast. *Medical Journal of Australia* **1**, 490-492.

Lincoln-Smith, M.P. and Smith, A.K. (1993). 'A survey of cysts of toxic dinoflagellates in sediments in Port Jackson, Botany Bay and Port Kembla'. A report prepared for the Australian Quarantine and Inspection Service, Canberra, Australia.

Lu, D., Zhang, Z., Zhu, G. and Lou, Y. (1994). Distributive pattern of *Noctiluca scintillans* in the Zhejiang coastal water area. *Donghai-Mar Sci.* Donghai Haiyang. **12**,62-69.

Marshall, J.A. and Hallegraeff, G.M. (1999). Comparative ecophysiology of the harmful algal *Chattonella marina* (Raphidophyceae) from South Australia. *Journal of Plankton Research* **21**, 1809-1822.

McLachan, A. and Hesp, P. (1984). Surf zone diatom accumulations on the Australian coast. *Search*, **15**, 230-231.

Moestrup, O. (1994). Economic Aspects: "blooms", nuisance species and toxins. In 'The Haptophyte Algae' (Eds. J. C. Green and B. S. C Leadbeater). Systematics Association Special Volume No. 51, pp. 265-285. (Clarendon Press: Oxford).

Murray, S. and Suthers, I.M. (1999). Population ecology of *Noctiluca scintillans* Macartney, a red-tide-forming dinoflagellate. *Journal of Marine and Freshwater Research* **50**, 243-52.

Nielsen, M.V. (1993). Toxic effect of the marine dinoflagellate *Gymnodinium galatheanum* on juvenile cod *Gadus morhua*. *Marine Ecology Progress Series* **95**, 273-277.

Okaichi, T. (1985). Fish kills due to the red tides of *Chattonella*. *Bulletin Marine Science* **37**, 772.

Okaichi, T. and Nishio, S. (1976). Identification of ammonia as the toxic principle of red tide of *Noctiluca miliaris*. *Bulletin of Plankton Society of Japan* **23**, 25-30.

Oviatt, C., Lane, P., French, F. and Donaghay, P. (1989). Phytoplankton species and abundance in response to eutrophication in coastal marine mesocosms. *Journal of Plankton Research*. **11**, 1223-1244.

Pan, Y. and Rao, S. (1997). Impacts of domestic sewage effluent on phytoplankton from bedford Basin, Eastern Canada. *Marine Pollution Bulletin* **34**, 1001-1005.

Pritchard, T., Lee, R. and Ajani, P. (1999). Anthropogenic and oceanic nutrients in NSW's dynamic coastal waters and their effect on phytoplankton populations. 14th Australian Coastal and Ocean Engineering Conference and the 7th Australasian Port and Harbour Conference – Coasts and Ports 1999.

Porumb, F. (1992). On the development of *Noctiluca scintillans* under eutrophication of Romanian Black Sea waters. In

'Marine Coastal Eutrophication'. Proceedings of an international conference, (Eds Vollenweider, R. A., R. Marchetti, R. Viviani). Bologna, Italy. 21-24 March, 1990, pp. 907-918. (Elsevier: Amsterdam).

Pritchard, T.R., Lee, R.S. and Ajani, P. (1997). Oceanic and Anthropogenic Nutrients and the Phytoplankton Response: Preliminary Findings. Pacific Coasts and Ports '97 Proceedings,V1. (CAE University of Canterbury, Christchurch, New Zealand).

Qi, Y., Zhang, Z., Hong, Y., Lu, S., Zhu, C. and Li, Y. (1993). Occurrence of red tides on the coasts of China. In 'Toxic Phytoplankton blooms in the sea' (Eds T. J. Smayda and Y. Shimizu) pp. 43-46 (Elsevier: New York).

Quilliam, M., Eaglesham, G., Hallegraeff, G., Quaine, J., Curtis, J., Richard, D., and Nunez, P. (2000). Detection and identification of toxins associated with a shellfish poisoning incident in New South Wales, Australia. In: 'Harmful Algal Blooms 2000. Proc. 9th Int. Conf. Harmful Algal Blooms'. (Eds G.M.Hallegraeff, S.I.Blackburn, C.J. Bolch and R.J. Lewis). (IOC. Paris).

Rensel, J.E. (1993). Severe blood hypoxia of Atlantic salmon (*Salmo salar*) exposed to the marine diatom *Chaetoceros concavicornis*. In: Toxic Phytoplankton Blooms in the sea. (Eds. T. J. Smayda and Y. Shimizu) pp 625-630. (Elsevier: New York).

Rensel, J.E., Horner, R.A. and Postel, J.R. (1989). Effects of phytoplankton blooms on salmon aquaculture in Puget Sound, Washington: initial research. *Northwest Environmental Journal* **5**, 53-69.

Riegman, R., Noordeloos, A.M. and Cadee, G.C. (1992). *Phaeocystis* blooms and eutrophication of the continental coastal zones of the North Sea. *Marine Biology* **112**, 479-484.

Richardson, D.L. (1991). Some aspects of food and feeding in the Sydney Rock Oyster *Saccostrea commercialis* in Port Stephens. B.Sc. Honours thesis, University of New England, New South Wales.

Smayda, T.J. (1990). Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic. In 'Red tides – Biology, Environmental Science and Toxicology' (Eds T. Okaichi, D. Anderson and T. Nemots). (Elsevier: New York).

Smayda, T.J. (1997). Harmful algal blooms: Their ecophysiology and general relevance to phytoplankton blooms in the sea.'*Limnology and Oceanography* **42**, 1137-1153.

Sournia, A., Chretiennot-Dinet, M.J. and Ricard, M. (1991). Marine phytoplankton: how many species in the world ocean? *Journal of Plankton Research* **13**, 1093-1099.

Staver, K.W. and Brinsfield, R.B. (1996). Seepage of groundwater nitrate from a riparian agroecosystem into the Wye River estuary. *Estuaries*. **19**, 359-370.

Takano, H. (1956). Harmful blooming of minute cells of *Thalassiosira decipiens* in coastal waters in Tokyo Bay. *Journal of Oceanographical Society of Japan*. **12**, 63-67.

Taylor, F.J.R. (1990). Red tides, brown tides and other harmful algal blooms: the view into the 1990's. In 'Toxic Marine Phytoplankton' (Eds. E. Graneli et al). (Elsevier: New York).

UNESCO (1995). *Manual on harmful marine microalgae*. Eds. G.M. Hallegraeff, D.M. Anderson, A.D. Cembella and H.O. Enevoldsen.

UNESCO (1996). *Design and Implementation of some harmful algal monitoring systems*. International Oceanographic Committee Technical Series No. 44.

Velikova, V., Moncheva, S. and Petrova, D. (1999). Phytoplankton dynamics and red tides (1987-1997) in the Bulgarian Black Sea. *Water Science and Technology*. **39**, 27-36.

Ward, T., Butler, E. and Hill, B. (1998). 'Environmental indicators for national state of the environment reporting'– estuaries and the sea'. State of the Environment (Environmental Indicator Reports), Department of the Environment, Canberra.

Whitelegge, T. (1891). On the recent discoloration of the waters of Port Jackson. *Recordings of the Australian Museum*. **1**, 179-192.

Yang, C.Z., Albright, L.J. and Yousif, A.N. (1995). Oxygen-radical mediated effects of the toxic phytoplankter *Heterosigma carterae* on juvenile rainbow trout *Oncorhynchus mykiss*. *Dis. Aquatic Organisms* **23**, 101-108.